An Analytical Modelling Approach to Test if a Rising Salt Diapir Triggered The Cape Fear Landslide

THESIS

Presented in Partial Fulfillment of the Requirements for the Degree Master of Science in the Graduate School of The Ohio State University

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The Ohio State University
2015

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Abstract

Recently acquired 2-D seismic data from offshore North Carolina provides images of salt diapirs and landslides in the region of the Carolina Trough that give insight into the interaction between slope sediments and intruding salt from below. The best example of this is the Cape Fear Slide Complex in which the lower headwall of the slide surrounds at least two salt diapirs. Here, we present seismic images that were collected for the Eastern North American Margin Community Seismic Experiment, which we use to gain new insights into the sedimentary features present in this area, including new evidence for the location of the top of salt of the Cape Fear diapir (approximately 665 meters below seafloor). In addition, we analyze the morphology of the slide and Cape Fear diapir, and use an analytical model to infer a rate of vertical salt rise both before and after the occurrence of the Cape Fear landslide. Using this method we have estimated post-failure growth rates of 357 meters per million years (m/Ma), and pre-failure growth rates of 319 m/Ma. Furthermore, based on the post-failure salt growth rate we estimate that the salt has only risen between 4 and 10 meters since the landslide happened, assuming the published age range for the landslide. With this in mind, further analysis of the slope geometries on the flanks of the Cape Fear diapir mound prompt us to suggest that it is highly unlikely for the rise of salt itself to have triggered the Cape Fear landslide through oversteepening. Instead we believe there to be a more complex story, in which the salt
may have primed this area of slope for failure while another mechanism, such as
dissociating gas hydrates or an earthquake may have acted as the eventual trigger of the
Cape Fear event.
Acknowledgements

Firstly, I would like thank Mahdi Heidari and Maria Nikolinakou, from the University of Texas, Austin for providing me with their analytical model, which has become such a key part of my work. I would also like to thank them for helping me with adapting their model to the Cape Fear salt-slide system and always being able to assist me with using their model as well. Additionally, I appreciate the work done by the science party and crew aboard the R/V Langseth for the GeoPRISMS Eastern North American Margin (ENAM) Community Seismic Experiment, which was funded by the NSF, as their work has provided me with the seismic data needed for my research. I am also very greatful to the Geological Society of America (GSA) for their offer to fully fund my research, and to the Friends of Orton Hall fund from The Ohio State University, School of Earth Sciences for providing funding that allowed me to travel to various conferences to present my work. Most importantly though, I would like to thank my advisor, Dr. Derek Sawyer, for guiding me throughout my Master’s journey, and always being willing to help fund various travel opportunities to advance my career and further my scientific knowledge.
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Publications

Akinci L, Sawyer D. 2016. Deriving the Rate of Salt Rise at the Cape Fear Slide Using
New Seismic Data. Submarine Mass Movements and Their Consequences, 7th

Fields of Study

Major Field: Earth Sciences
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Introduction

A link between salt movement and slope failures has been well documented in several locations around the world, particularly in the Gulf of Mexico, as demonstrated by Angell et al. (2003), Orange et al. (2003), Tripsanas et al. (2004) and Kovacevic et al. (2012) among others. Most commonly, salt triggers slope failures when it rises and causes oversteepening of overlying sediments. This occurs because as the salt rises it shoulders the overlying sediments aside, resulting in a build-up of sediments around the salt body. Because shear stress increases as slope angle increases, eventually, these sediments may be built-up to a point where the shear stress overcomes the shear strength of the sediments, resulting in a slope failure.

A key problem remaining today is understanding the interplay and feedbacks between salt diapirism and slope failure processes. In particular, there has been little research into how a diapir may react to the removal of overburden, such as where a landslide has occurred. Part of the problem is quantifying the rate of salt rise, as there are several complexities associated with salt flow, such as its three dimensionality and movement irregularities.

These coupled salt-slide processes are important for understanding how submarine landslides occur in salt basins. Salt basins are common in both modern and ancient periods and thus may suggest a significant fraction of submarine landslides are
related to salt tectonics. This is important as submarine landslides can generate tsunamis, and therefore have a significant impact on coastal communities worldwide. Therefore understanding how the seafloor reacts in various scenarios, for example, where a salt diapir is rising beneath a continental slope, is particularly important for coastal communities around the world. Moreover, with a growing number of people on the Earth overall, and a greater percentage of the Earth’s population choosing to locate along coasts (Hinrichsen, 1998), understanding how natural events impact coastal areas becomes of even greater importance, as a growing proportion of people will be affected by them. As such, by developing a better understanding of the seafloor and the mechanics behind slope failure, perhaps coastlines that are more likely to be affected by devastating events that cause tsunamis could be identified. This would help to provide the information necessary to better prepare these areas for the occurrence of such events.

In order to gain insight into the feedbacks between salt diapirism and removal of overburden, we investigate a submarine landslide, the Cape Fear landslide, off the coast of North Carolina, which is associated with a rising salt diapir. Dillon et al. (1982), Cashman and Popenoe (1985), Popenoe et al. (1993), among others have suggested a possible link between the rising salt and failure of the Cape Fear landslide here. One of the prevailing theories suggests that as the diapir rose, it initiated the Cape Fear landslide by oversteepening the sediments on the downslope flank of the sediment mound above the diapir (fig. 1) (Cashman and Popenoe, 1985). The landslide is then believed to have retrogressed from this point to the headwall seen today (Cashman and Popenoe, 1985; Hornbach et al., 2007).
One of our main goals has been to test the theory suggested by Cashman and Popenoe (1985) and determine if this scenario is plausible. Additionally, we wanted to know how the salt itself reacted to the removal of overburden due to the landslide by quantifying the rise rate of the salt. To investigate these ideas we use new seismic data acquired for the Eastern North American Margin (ENAM) community seismic experiment (fig. 2). The goal of ENAM is to understand the breakup of continents that
led to the formation and later evolution of the eastern edge of North America and the Atlantic Ocean. From this dataset we focus on seismic line 33-34 that images the Cape Fear salt-slide system to characterize the landslide and salt dome, and obtain crucial measurements, such as diapir dimensions and slope angles. Subsequently, we use an analytical model from Heidari et al. (In Review), along with the values achieved from the system characterization, to quantify the salt rise rate within this system. In doing so we
determine where the salt may have been at the time the landslide occurred, in order to
calculate the possible salt rise rate prior to the occurrence of the landslide. This allows us
to compare any changes in the rate of rise before and after the removal of overburden due
to the landslide. We can then also postulate whether the salt did actually trigger the Cape
Fear slide and consider what other factors may have come into play in the development
of the Cape Fear event.
Geologic Setting

Off the coast of North Carolina, the continental slope and upper continental rise overlie a sedimentary basin known as the Carolina Trough. This is a narrow sediment filled basin that formed when North America and Africa first began rifting apart during the Jurassic Period. In its early history, local conditions allowed for the deposition of a thick layer of salt (Dillon et al., 1982; Hutchinson et al. 1983). According to Dillon et al. (1982) this occurred here possibly because greater stretching during rifting resulted in a thinner basement, and thus earlier subsidence below sea level than other basins off the eastern North American margin, giving the salt a longer length of time to deposit.

Following evaporite deposition, prograding sediments from the continental shelf filled the basin from the west. This asymmetrically loaded the salt (Popenoe et al., 1993) (fig. 3B). This caused the salt to flow eastward until shallower basement at the eastern edge of the Carolina Trough forced the salt upwards (fig. 3C) into a line of diapirs (Cashman and Popenoe 1985; Popenoe et al. 1993) (fig. 3D). Subsidence due to salt withdrawal from beneath the basin into the diapirs also led to the formation of a large regional fault along the Carolina Trough’s western margin (Dillon et al., 1982) (fig. 3D)

Salt flow

A long standing theory in salt tectonics was that salt flow was dominated by salt buoyancy. However modern interpretations have stressed that differential loading seems
Figure 3. Conceptual sketch of diapir development within the Carolina Trough. A, rifting of Carolina Trough during Jurassic period, leading to accommodation space for salt deposition (salt shown in black); B, asymmetrical loading of salt due prograding sediments from the west, leading to eastward flow of salt; C, Basement obstruction at the eastern edge of the Carolina Trough begins to force salt upwards; D, With continued sedimentation, density differences between the salt and surrounding basin sediments allow the salt to continue rising, causing salt withdrawal from within the trough and thus basin subsidence. This causes the formation of a large normal fault (shown by red line) along the west side of the Trough.

to be the dominant driving force behind salt flow (Hudec and Jackson, 2007). In the case of the Carolina Trough, differential loading occurred when sediments began filling in the western side of the trough first, as they were prograding eastward. This resulted in a much thicker body of sediment overlying the western side of the trough, compared to the eastern side of the trough. As such, a pressure head gradient (Ge et al., 1997; Hudec and Jackson, 2007) was created between the Western and Eastern side of the trough, where the pressure head was much higher on the Western side of the trough, than the Eastern side of the trough, due to the greater sediment thickness (fig. 4). Since salt always flows
Figure 4. A laterally varying overburden thickness above a horizontal, tabular salt layer produces a pressure head gradient from Point 1 to Point 2 but no elevation head gradient. Salt will flow from left to right along the pressure head gradient (Hudec and Jackson, 2007).

from areas of higher pressure head to areas of lower pressure head (Hudec and Jackson, 2007), this resulted in the flow of salt from west to east.

In the Carolina Trough, this west-east flow of salt was inhibited by the eastern margin of the trough, resulting in the initiation of diapir formation. This is important to note as typically a flat body of salt will not begin to form a diapir without some sort of deformation or displacement as an impetus (Shultz-Ela et al., 1993; Hudec and Jackson, 2007; Hudec and Jackson, 2012). Once a diapir originates, there are several stages of diapirism that may ensue.

First, reactive diapirism may occur (fig. 5b), which is where a diapir rises to infill accommodation formed in response to regional extension (Vendeville and Jackson, 1992). As extension was likely to be actively occurring during the initial emplacement of salt into diapirs within the Carolina Trough (Dillon et al. 1982; Dillon and Popenoe, 1988), previous work has suggested that diapirs here may have initially formed in a reactive way (Hornbach et al., 2007).
Figure 5. Diapir piercing during regional extension. Diapirs do not necessarily progress through all of these stages. The maturity of a given structure depends on availability of salt, total amount of extension, and relative rates of extension and sedimentation (Hudec and Jackson, 2007).

Without extension however, diapirs have to overcome the resistance of overburden strength in order to continue to intrude overlying strata, in a process known as active diapirism (Shultz-Ela et al., 1993; Hudec and Jackson, 2007) (fig. 5c), which can occur if basin overburden exudes sufficient pressure on the salt feeding the diapir. Dillon et al., (1988) suggests that up-warping of the seafloor above the Cape Fear diapir may be evidence of such active diapirism currently taking place in the Carolina Trough.
Finally, once a diapir has broken through to the surface, passive diapirism may ensue (fig. 5d), which is the syndepositional rise of salt in conjunction with surrounding sediments (Jackson and Talbot, 1991; Hudec and Jackson, 2007). However, it remains unclear if diapirs in the Carolina Trough have experienced a passive stage in their history. Nonetheless, the upward movement of salt into diapirs has resulted in subsidence within the Carolina Trough due to the withdrawal of salt from beneath the basin (Dillon et al., 1982). As such, a large growth fault has formed along the western boundary of the trough (Dillon et al., 1982).

The Cape Fear Landslide

The main headwall of the Cape Fear slide is a 50 km long (Popenoe et al. 1993), amphitheatre-shaped scarp that is up to 123 m high, at a water depth of approximately 2500 m. From here, mass-movement deposits extend 400 km or more downslope, where water depths exceed 5400 m on the abyssal plain (Popenoe et al. 1993). Furthermore, the main headwall circumscribes at least two large salt diapirs (fig. 6). The larger of the two diapirs can be seen on side scan sonar imagery of the Cape Fear slide, where there are clear flow lines extending approximately east (downslope) from the diapir (fig. 6) (Popenoe et al., 1993). Further downslope there is evidence of a highly fluidized flow, because of the long run out on a very low seafloor gradient (fig. 6).

The Cape Fear slide is not simply a single failure event. Though one large event occurred first and formed the present day main headwall, there is evidence of subsequent slope failures farther upslope (Popenoe et al., 1993; Hornbach et al., 2007). At least 4 additional failure scarps have been identified besides the main head scarp using multibeam bathymetry and shallow chirp data (fig. 7) (Hornbach et al., 2007). Based on
the analysis by Hornbach et al. (2007), following the main Cape Fear slide event, a second slide occurred just north of the initial slide, but at the same approximate depth, and even overlaps some of the area that failed in the initial slide. Following this, a third slide occurred that marks the most westerly and shallowest extent of slope failures within the Cape Fear slide complex (Hornbach et al., 2007). The head scarp formed by this event is at approximately 880 m in depth is located almost exactly at the shelf-slope break. Within the failed area of the third slide, there are a further two smaller slides as well (Hornbach et al., 2007).
Figure 7. A proposed scenario for relative slide timing based on the overlap and location of different slide headwalls (modified from Hornbach et al., 2007).
Methods

Seismic Interpretation

The first part of our investigation involved characterizing both the landslide and the salt diapir from the ENAM seismic data. It should also be noted that as seismic data had not been collected in this area since the 1980’s, the ENAM data provided the best quality and highest resolution seismic data available for this region. This seismic data was acquired in the fall of 2015, using a 3300 in$^3$ air gun array towed at a depth of 6 m (Cruise Report, 2014). Additionally, a 6 km streamer with a bin spacing of 12.5 m was used at a sample rate of 1 ms, while the shot interval was 25 m and record length 9 s (Cruise Report, 2014). During onboard processing of the raw seismic data broad filters were used to reduce low-frequency noise, and approximately 10% of the traces were bad and thus had to be killed (Cruise Report, 2014). Once cleaned, shot gathers were sorted into CDP gathers for velocity analyses, so that the data could be stacked and migrated (Cruise Report, 2014). In this process the multiple was muted out as well, in order to produce cleaner data (Cruise Report, 2014).

Using the processed seismic line 33-34 we identified the main headwall of the Cape Fear landslide and the salt diapir (fig. 8). These features were then cross referenced with previous characterizations based on older seismic data and side scan sonar imagery (Dillon et al., 1982; Popenoe et al, 1993). We then proceeded to measure water depths, diapir dimensions, the main headwall height and slope angles (fig. 9).
Figure 8. Seismic line 33-34, from ENAM data. Top version uninterpreted, while bottom version annotated. This line runs through the headwalls of the Cape Fear landslide and the Cape Fear diapir, which is shaded in pink. Though ODP site 991 is marked on this line, its exact location sits just off of this line, on the flank of the diapir, and not actually at the diapir’s crest. See fig. 9 for inset shown in red box. See fig. 2 for line location (A - A’).
Figure 9. Zoom in of line 33-34. Area shown is indicated by the red box on fig. 8. Here measurements of the diapir, diapir mound and landslide headwall are indicated. These measurements are used in later calculations.
Calculating the Salt Rise Rate

To calculate the present day rate of rise of the salt diapir, we used an analytical model that describes salt dome evolution in density-driven, rising salt domes (Heidari et al., In Review). For this model, salt is a viscous fluid, and diapirs are assumed to be upright and cylindrical in shape (Heidari at al., In Review). Then, based on Poisseuille’s flow through the salt dome the mean velocity of salt flow can be calculated. This equates to the rate of rise of the salt. The calculation is done by dividing the cross-sectional area of the diapir by the sum of salt viscosity and diapir height, then multiplying that by the difference of the overburden stresses of the basin, salt dome and roof sediments. This is expressed using the following equation:

\[
\dot{H} = \frac{K \cdot D^2}{\mu \cdot H} \left( \sigma_{ob,\text{basin}} - \sigma_{ob,dome} - \sigma_{ob,\text{roof}} \right)
\]

(Equation 1.)

Table 1. Nomenclature (Heidari et al., In Review)

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
<th>Dimensions</th>
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<tbody>
<tr>
<td>(H)</td>
<td>Rate of dome rise</td>
<td>LT(^{-1})</td>
</tr>
<tr>
<td>(K)</td>
<td>Dome shape factor for Poiseuille’s flow</td>
<td>–</td>
</tr>
<tr>
<td>(D)</td>
<td>Dome diameter</td>
<td>L</td>
</tr>
<tr>
<td>(\mu)</td>
<td>Salt viscosity</td>
<td>L(^{-1})MT(^{-1})</td>
</tr>
<tr>
<td>(H)</td>
<td>Height of salt dome</td>
<td>L</td>
</tr>
<tr>
<td>(\sigma_{ob,\text{basin}})</td>
<td>Basin overburden stress</td>
<td>L(^{-1})MT(^{-2})</td>
</tr>
<tr>
<td>(\sigma_{ob,dome})</td>
<td>Dome overburden stress</td>
<td>L(^{-1})MT(^{-2})</td>
</tr>
<tr>
<td>(\sigma_{ob,\text{roof}})</td>
<td>Roof overburden stress</td>
<td>L(^{-1})MT(^{-2})</td>
</tr>
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</table>
where $\dot{H}$ is the rate of salt rise, $K$ is a shape factor for circular salt domes, $D$ is the diameter of the diapir, $\mu$ is the viscosity of salt, $H$ is the height of the diapir, and the $\sigma$ values are the overburden stress of the basin, salt dome, and roof sediments, respectively (Heidari et al., In Review) (table. 1). Here, the value for $K$ is taken to be 0.031, while $\mu$ is assumed at $1.0 \times 10^{20}$ Pa · s (White, 1991). $D$ was measured directly from the seismic data. $H$ was estimated based on a depth for the top of the horizontal, tabular salt body (salt source) within the Carolina Trough from Trehú (1989) (fig. 10). The ENAM seismic line that images the Cape Fear diapir does not image the salt in the bottom of the Carolina Trough, as it was optimized for higher resolution in shallower sections, which results in reduced penetration depth due to increased attenuation of the sound waves.

Figure 10. Conceptual diagram of the Cape Fear system showing measurements of basin and diapir that were used for calculations.
The overburden stress of the basin ($\sigma_{\text{ob,basin}}$), is the pressure being transmitted through the horizontal salt to the diapir (Heidari et al., In Review). To calculate $\sigma_{\text{ob,basin}}$ we integrated sediment bulk density over the height of the sediment above the horizontal salt (fig. 10) and multiplied this by gravity (eq. 2). This is because sediment density increases with depth due to compaction (Hudec et al., 2009). In order to find an appropriate density curve to use for this calculation, we used bulk density measurements from a core taken from ODP leg 164, site 991, which is located on the flank of the Cape Fear diapir mound (fig. 2 and fig. 8). However, this core only extends to a depth of almost 60 m, while our basin depth is 9390 m. As a result we combined Baldwin and Butler’s (1985) density curve for normally compacted shales to extrapolate to total depth (fig. 11). We then substituted the function of the density curve into the following integration:

$$\sigma_{\text{ob,basin}} = \int_{B_{\text{min}}}^{B_{\text{max}}} \rho_b g \, dz$$  \hspace{1cm} \text{(Equation 2.)}$$

where $B_{\text{max}}$ is the maximum basin depth, $B_{\text{min}}$ is the minimum basin depth (0), $\rho_b$ is the bulk density curve function and $g$ is gravity (Heidari et al., In Review). The overburden stress of the roof ($\sigma_{\text{ob,roof}}$) was calculated in the same way, using the same density curve, however the height of the roof above the diapir replaces the maximum basin depth in the formula. On the other hand, salt dome overpressure is calculated using a constant density.
Figure 11. Bulk density curve for the sediments around the area of the Cape Fear slide, based on bulk density measurements taken from ODP leg 164, site 991 (see fig. 2), then extrapolated to 10,000 m using a curve for normally compacted shales (Baldwin and Butler, 1985). The inset shows a zoomed-in view of the uppermost 100 m, where ODP Site 991 data occur. See appendix A for bulk density measurements.
of 2.17 g/cc, multiplying this by the diapir height and gravity, then adding this to the overburden stress of the roof sediments:

\[
\sigma_{ob,dome} = \sigma_{ob,roof} + \rho_s gH
\]

(Equation 3.)

where \(\rho_s\) is the density of salt.

**Age of the Cape Fear Slide**

The base of the Cape Fear slide has been identified at a depth of 2.1 meters below seafloor (mbsf) at site 991 by Rodriguez and Paull (2000) (fig. 12). Using carbon-14 dating, Rodriguez and Paull (2000) also noted that this hiatus in deposition spans 10 to 27 thousand years ago (fig. 13). Therefore, the Cape Fear landslide must have occurred within this time span.

**Figure 12.** Core photo of the upper most section of cores obtained from Site 991 of ODP leg 164. This core starts at the seafloor. Highlighted in the yellow boxes are the total section from which samples were taken to determine a sedimentation rate.
Figure 13. Depth vs. $^{14}$C age for the uppermost 3.0 m at Site 991. These $^{14}$C ages indicate a hiatus between 10 and 27 ka (from Rodriguez and Paull, 2000).

With this in mind, we could then evaluate equation 1 to derive the rate of salt rise over the timespan since the landslide. This gives the amount of vertical salt growth, and thus determines the pre-failure height of salt. We then used this information to recalculate equation 1 for the pre-failure rate of salt. Changes resulting from sedimentation (sedimentation rate taken from Rodriguez and Paull (2000), (fig. 13)) and differences in sea level (approximately 120 m lower) at the time are accounted for.
Results

New Insights from the Seismic Data

We mapped the diapir, the upper headwall of the landslide, landslide deposits, and listric faults that extend up the continental slope from the main headwall (fig. 8). There are also multiple bottom simulating reflectors (BSRs) seen in the seismic data, which mark the bottom of the gas hydrate stability zone. Associated with the BSRs are amplitude anomalies as well, which could suggest the presence of free gas trapped beneath hydrates (fig. 8).

A surprising finding was the position of the top of salt of the Cape Fear diapir – at 665 mbsf. This is much deeper than previously thought. In fact previous papers often cited the diapir itself as having breached the seafloor (Dillon et al., 1982; Cashman and Popenoe, 1985; Popenoe et al., 1993; Hornbach et al., 2007), however the higher resolution of the ENAM data set has illuminated a clear top of salt reflector that was not visible in previous seismic data from the area. It also resolves clear stratification above this reflector within a section that was believed to be composed of salt, which corroborates this new finding (fig. 8 And fig. 9).

Salt Rise Rate

From equation 1, the current (post-failure) rate of salt rise is 357 m/Ma (table 2). Based on this rate and using the upper and lower bounds for the age of the landslide we
then calculated that the salt has only grown approximately 4 to 10 m since the Cape Fear landslide occurred. With this the pre-failure rate of salt rise from equation 1 was 319 m/Ma (table 2).

The rate of salt rise increased by 12% following the removal of overburden. This is a relatively small increase, likely because the 123 m change in overburden is extremely small relative to the overall basin height (9390 m) and diapir height (7065 m). Both of which are key variables in determining the diapir rise rate.

Equation 1 provides an upper bound estimate of salt rise. This is due to simplifying assumptions, including ignoring roof strengthening (strengthening of the roof sediments resulting from compaction caused by the rise of the diapir; stronger roof sediments would inhibit salt vertical salt flow), and assuming sufficient salt supply from the base layer to allow salt to flow freely towards the diapir, all of which favor a higher rate of rise (Heidari et al., In Review). As a result, it is likely that the actual amount of salt growth since the landslide is less than the 4 to 10 m range that we report. However, when we compare our calculated rise rates with previously published salt growth rates as our results still fall within the range of growth rates calculated in other regions around the world (fig. 14).
Figure 14. Published rates of salt growth (adapted from Seni and Jackson, 1983). Growth rate of Cape Fear diapir has been included for comparison.
Discussion

Slope stability

A small change in salt height (4 – 10 m) since the Cape Fear landslide occurred means that the geometries we see today, specifically the maximum slope angle on the flank of the diapir mound present the geometries at the time of failure. This maximum angle is 7°, which is well below the angle of repose (~25°) for these sediments (Komar, 1978; Hannan, 2006). Therefore, the slope here would have been stable at hydrostatic conditions. Failure could only have occurred if there was an additional mechanism to generate overpressure.

We calculated the amount of overpressure required to generate a slope failure at 7°. This involved using the failure ratio equation to calculate the overpressure ratio based on the effective stress at the given depth of failure (123 m – based on headwall measurement (fig. 9)) (See appendix B for full calculation derivation). We found the calculated overpressure ratio to be 0.74, meaning pore pressure had to equal at least 74 % of the effective stress in order for a slope failure to occur on the flank of the Cape Fear diapir (fig. 15).

To see if the rising salt could generate an appropriate amount of overpressure, we compared our calculated rate of rise to hydraulic conductivity, which is the rate at which fluids can flow through the sediment. However as there are no hydraulic conductivity measurements from the Carolina Trough area, we used measurements from similar
marine sediments offshore New Jersey (Dugan et al., 2000; Blum et al., 1996). From Blum et al. (1996) and Dugan et al. (2000) the hydraulic conductivity is 0.3 mm/yr, while the rate of salt rise is only 0.013 mm/yr. This is more than 20 times less than hydraulic conductivity, which means it would be highly unlikely, even assuming a large margin of error, that the salt would be able to generate any overpressure in overlying roof sediments – the pressure would have simply bled off without building up at all.

**Figure 15.** Pressure, depth plot of the Cape Fear landslide sediments prior to failure of landslide. Failure point indicated by red marker shows the pressure that would have been required to initiate the Cape Fear landslide at the given 7° slope angle.
As a result, we explain that the salt could not have triggered the Cape Fear landslide through oversteepening – the salt has simply not risen high enough nor fast enough to generate the conditions required to trigger a slope failure by itself. However, the salt did play an important role in priming this location for a slope failure, as it still managed to create the steepest slope in the area. Inevitably this made the 7° slope more likely to fail when compared to the surrounding seafloor, as this slope is still the most unstable in the area. Regardless, other trigger or triggers must have occurred.

Possible Landslide Triggers

Another often-cited trigger for the Cape Fear landslide is gas hydrates (Carpenter, 1981; Schmuck and Paull, 1992; Popenoe et al., 1993; Hornbach et al., 2007). This is because there is extensive evidence of gas hydrates in this area in the form of bottom simulating reflectors (BSRs) seen on seismic data (fig. 16), which mark the base of hydrate stability. Additionally, hydrate samples have been obtained in cores taken from Blake Ridge, approximately 125 km south of ENAM line 33-34. This, along with the fact that the Cape Fear landslide occurred sometime during the last sea-level lowstand, have prompted some to suggest that the dissociation of hydrates at that time could have generated sufficient overpressure in sediments to cause the slope failure. It is also possible that the salt could have further conditioned the slope for failure here as salt has high thermal conductivity relative to sediments, and thus may have aided in faster dissociation of gas hydrates immediately surrounding the salt (Cashman and Popenoe, 1985).

Earthquakes are a potential trigger because, there is significant seismic activity around South Carolina (Cutter et al., 2000). In particular some have cited the famous
1886 Charleston, South Carolina earthquake as the possible trigger for the Cape Fear slide (Embley, 1980; Carpenter, 1981). However, as we have seen from dating of the slide (Rodriguez and Paull, 2000), the Cape Fear event predates this earthquake by tens of thousands of years. Having said this, a large earthquake occurring within the time span claimed by Rodriguez and Paull still cannot be ruled out (Popenoe et al., 1993).

Figure 16. Zoomed in image of seismic data to highlight the BSRs within the section.
Future fate of the Cape Fear Salt-Slide Complex

From the Heidari et al. (In Review) analytical model, we can also determine the critical sedimentation rate (rate at which diapir and sediments rise at the same rate) for a diapir of a given diameter, based on the thickness of the basin (fig. 17). This relationship is directly proportional, so as basin thickness increases, the critical sedimentation increases too, for any given diapir diameter. However, the greater the diapir diameter is,

![Figure 17](image)

**Figure 17.** Extrusion of the Cape Fear diapir is expected to continue in the future. The line on the graph marks the critical sedimentation rate for a diapir that is 4.79 km in diameter (the diameter of the Cape Fear diapir) at any given basin thickness. The area above the line represents conditions where diapir burial would occur, while the area below the line represents conditions where diapir extrusion would occur. The yellow star marks the conditions seen at the Cape Fear diapir today. Adapted from Heidari et al. (In Review).
the faster the critical sedimentation rate rises with respect to increasing basin thickness. Looking at figure 17, any points that fall below the critical sedimentation line indicate conditions where diapir extrusion is expected. Any points above the line indicate conditions where diapir burial is expected. So as we can see, for the Cape Fear diapir, based on basin thickness estimates from Trehú (1989) and sedimentation rates from Rodriguez and Paull (2000), the diapir is expected to continue to extrude. This indicates continued growth of the Cape Fear diapir in the future. With that in mind, we may then expect that at some point in the future, the diapir may rise enough to generate slope failures by simply oversteepening the slope.
Conclusion

With new seismic data we have made new insights into the relationships between salt diapirs and submarine landslides. Most prominently we identified a top of salt for the Cape Fear diapir at a depth of 665 mbsf, which is drastically different to the previous assumption that the salt had actually breached the seafloor here. Instead we find that the still buried diapir has distorted overlying strata, forming a sediment mound that rises above the surrounding seafloor.

Moreover, we presented a new way to investigate the interactions between rising salt and a submarine mass movement, using an analytical model developed by Heidari et al. (In Review). Our method allowed us to quantify the rate of salt rise and compare how this changed in response to the Cape Fear landslide. In doing so we found that the rate of salt rise was barely affected by the removal of overburden in this case, mostly likely because the amount of overburden removed was only a tiny fraction of the total basin depth and diapir height.

Finally, our findings also cast major doubt on the theory that the rising salt may have triggered the Cape Fear landslide by oversteepening the overlying sediments. This is because we found that the slope above the diapir should have been stable at hydrostatic conditions, and so overpressure conditions must have
been at play here. However, we also found that the salt most likely could not
generate such overpressures as it rose, leading us to believe the situation is one that
is more complex, where multiple factors contributed to the occurrence of the Cape
Fear landslide. Along these lines we suggest that the salt probably primed the slope
for failure, while another mechanism, such as dissociating gas hydrates or an
earthquake may have acted as the eventual trigger of the Cape Fear event.
References


Dillon WP, Popenoe P, Grow JA, Klitgord KD, Swift BA, Paull CK, Cashman KV. 1982. Growth faulting and salt diapirism: Their relationship and control in the Carolina Trough,


### Appendix A: Bulk Density Values From ODP Leg 164, Site 991

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Appendix B: Calculating Overpressure Ratio (Hubbert and Rubey, 1959)

1. Rearrange the failure ratio equation in terms of normal effective stress ($\sigma_{N'}$):

$$\frac{\tau}{\sigma_{N'}} = \mu \rightarrow \sigma_{N'} = \frac{\tau}{\mu}$$

where $\mu$ is the coefficient of friction, and $\tau$ is shear stress. This gives the ratio of normal to shear stresses at failure for a slope at friction angle.

a. $\mu$ is derived by finding the tangent of the friction angle ($\phi$):

$$\mu = \tan \phi$$

For Cape Fear sediments, $\phi$ has been assumed as 25°, typical of marine mud.

b. $\tau$ is derived by multiplying the normal effective stress ($\sigma_{N'}$) by the sine of the angle of the slope under investigation ($\theta$):

$$\tau = \sigma_{N'} \cdot \sin \theta$$
For Cape Fear, $\theta$ is $7^\circ$ as this is the angle of the slope where the landslide is believed to have initiated. In this case $\tau = 94$ kPa.

i. Here, $\sigma_{N'}$ is derived by subtracting the hydrostatic pore pressure $(P_h)$ from the total stress $(\sigma_T)$ at the given depth of failure:

$$\sigma_{N'} = \sigma_T - P_h$$

In this case, $\sigma_T$ is taken as the lithostatic pressure at the given failure depth (123 m), and $P_h$ is taken as the hydrostatic pressure at the failure depth (fig. 15). For Cape Fear this $\sigma_{N'} = 0.769$ MPa

2. Calculate the normal effective stress at failure $(\sigma_{N'})$ in terms of $\mu$ and $\tau$:

$$\sigma_{N'} = \frac{\tau}{\mu}$$

At Cape Fear this $\sigma_{N'} = 0.202$ MPa

3. Use this $\sigma_{N'}$ to calculate pore pressure $(P_p)$ by subtracting normal effective stress $(\sigma_{N'})$ from normal stress $(\sigma_N)$:

$$P_p = \sigma_N - \sigma_{N'}$$
Note that $\sigma_N = \sigma_T$ here. In this case $P_p = 25.770$ MPa

4. Use the answer for $P_p$ to calculate the overpressure ratio ($\lambda^*$) as follows:

$$\lambda^* = \frac{P_p - P_h}{\sigma_T - P_h}$$

For the Cape Fear system $\lambda^* = \frac{25.770 - 25.203}{25.972 - 25.203} = 0.74.$